

## Resolving the Origin of the Diffuse Soft X-ray Background

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In January 1993, the Diffuse X-ray Spectrometer (DXS) measured the first high-resolution spectrum of the diffuse soft X-ray background between 44-80 Å<sup>1</sup>. A line-dominated spectrum characteristic of a 10<sup>6</sup>K collisionally ionized plasma<sup>2</sup> was expected but while the observed spectrum was clearly line-dominated, no model would fit. Then in 2003 the Cosmic Hot Interstellar Plasma Spectrometer (CHIPS) launched and observed the diffuse extreme-ultraviolet (EUV) spectrum between 90-265 Å. Although many emission lines were again expected, only Fe IX at 171.1 Å was detected<sup>3</sup>. The discovery of X-rays from comets led to the realization that heavy ions ( $Z=6-28$ ) in the solar wind will emit soft X-rays as the ions interact via charge exchange with neutral atoms in the heliosphere and geocorona<sup>4,5</sup>. Using a new model for solar wind charge exchange (SWCX) emission, we show that the diffuse soft X-ray background can be understood as a combination of emission from charge exchange onto the slow and fast solar wind together with a more distant and diffuse hot (10<sup>6</sup>K) plasma.

Despite being one of the first discoveries of X-ray astronomy<sup>3</sup>, the origin of the soft X-ray background has stubbornly remained a mystery. Maps in a range of soft X-ray bands show that the emission is apparently unabsorbed<sup>2</sup> with both a constant and a time-variable component<sup>6</sup>. Optical data show that a “Local Bubble” (LB) of low-density gas surrounds the Sun<sup>7</sup> out to ~100 pc, which if filled with a diffuse 10<sup>6</sup>K thermal gas – the so-called “Local Hot Bubble” (LHB) – would explain the soft X-ray background. However, models that would create such hot gas with supernova shock waves have problems matching the observed X-ray intensity and spectrum, and the implied pressure needed to generate the emission is quite large<sup>2,7</sup>. The DXS data complicates the issue further as no collisional thermal plasma model, either in equilibrium or out, adequately characterized the observations<sup>1</sup>.

The discovery of significant SWCX in comet spectra<sup>4</sup> led to suggestions that this process could also be involved in creating the soft X-ray background<sup>5</sup>. Cravens<sup>8</sup> developed an analytic model that combined known solar wind ions with interstellar neutral atoms flowing through the heliosphere. This model predicted that up to 50% of the soft X-ray background could be explained by SWCX. More detailed models of the solar wind ions and the neutral H and He in the heliosphere<sup>9</sup> have extended these results to suggest that SWCX could contribute nearly all the flux in some directions, although these have used comparisons only to broad-band fluxes and not the higher resolution spectra from the DXS and CHIPS observations.

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The DXS experiment flew on the STS-54 mission (January 13-19, 1993), mounted in the Space Shuttle payload bays. The detector used a pair of rocking Bragg-crystal spectrometers to obtain spectra of the diffuse X-ray background in the 44-84 Å (148-284 eV) range, with good  $\sim 2.2$  Å spectral resolution but limited  $\sim 15^\circ$  angular resolution. The results shown here include data from the port instrument (the starboard detector had in-flight problems) that were taken while observing low-Galactic latitude regions between from  $0$ - $20^\circ$ , at Galactic longitudes  $160^\circ$ - $180^\circ$  and  $225^\circ$  -  $250^\circ$ . These regions were chosen as they are dominated by diffuse emission with no significant individual X-ray sources.

The CHIPS satellite was launched in January 2003, providing six independent gratings with a rectangular  $5^\circ \times 25^\circ$  field of view covering the 90-265 Å bandpass with a peak resolution of 1.4 Å<sup>4</sup>. CHIPS was designed to observe lines from Fe VIII-Fe XII in the range 168-195 Å, which were predicted to be extremely bright ( $150$ - $200$  photons  $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ , hereafter 'line units', LU), comprising up to 50% of the total power from a LHB<sup>10</sup>. In over a year of observations, CHIPS observed many locations, primarily at high Galactic latitudes, but detected only one line, from Fe IX at 171.1 Å, in about 10% of observations with a flux of  $>10$  LU. The combined 13.2 Msec spectrum has systematic limits around 6 LU, which provide a tight constraint on any proposed model. Other similar limits exist using different techniques. The ALEXIS satellite, launched in 1993, used an imaging narrow-band filter that put  $1\sigma$  limits of  $\sim 20$  LU on any non-variable emission in the  $\sim 170$ - $185$  Å bandpass<sup>10</sup>. Finally, the X-ray Quantum Calorimeter (XQC) sounding rocket also measured diffuse soft X-rays towards a high-latitude line of sight, measuring Fe IX-XI emission at  $\sim 171$  Å of  $100 \pm 50$  LU along with C VI, O VII, and O VIII of  $5.4 \pm 2.3$  LU,  $4.8 \pm 0.8$  LU, and  $1.6 \pm 0.4$  LU, respectively<sup>11</sup>. The XQC detection of emission at 171 Å is inconsistent with the CHIPS and ALEXIS non-detections but is based on a small number of counts. In addition to these EUV and soft X-ray observations, the Chandra, XMM-Newton, and Suzaku observatories have also measured diffuse soft X-rays towards nearby dark clouds that shadow more distant emission, typically measuring emission from O VII of between 0.3-4.6 LU and O VIII of less than 2.1 LU<sup>15</sup>, with large variations.

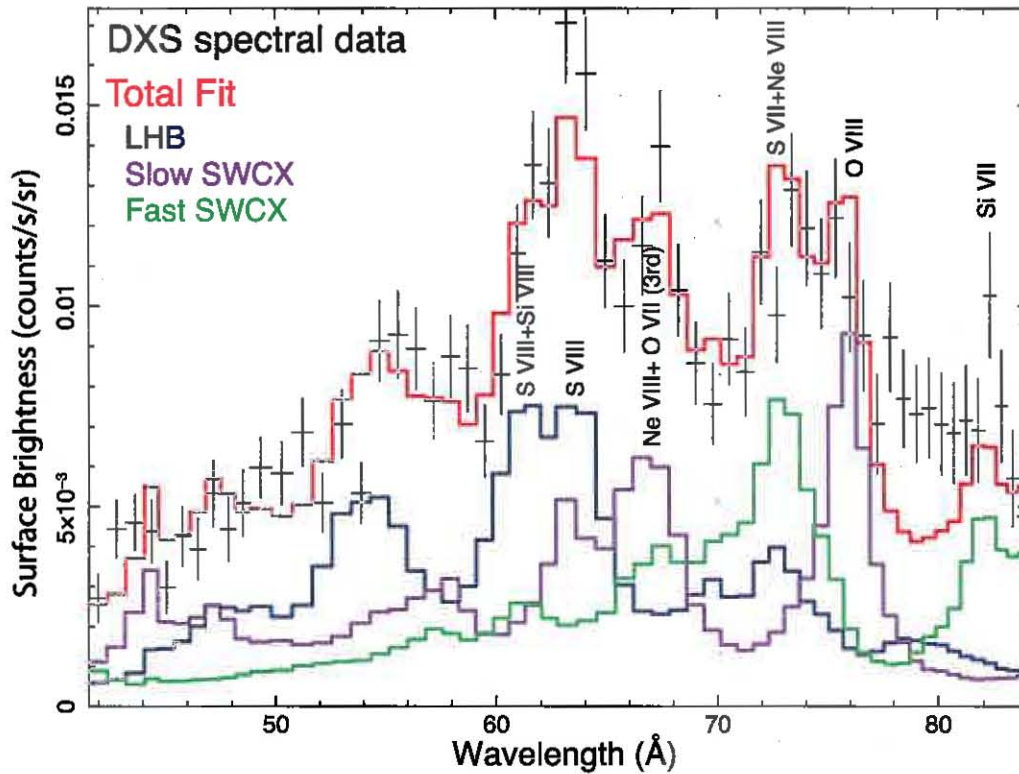


Figure 1: The DXS data fit (red curve) with the SWCX components (green, purple curves) plus the LHB (blue curve) model.

Using a new approach, we fit the DXS spectrum, together with the CHIPS upper limits, using a three-component model (see Figure 1). The LHB component was represented by a thermal plasma in collisional equilibrium<sup>12</sup> with abundances taken from those measured in nearby diffuse clouds<sup>13</sup>. The SWCX was modeled with emission from both the slow and fast solar wind, using elemental abundances typical of each component<sup>14</sup>. Figure 1 shows the best-fit model, fit using only six free parameters: the electron temperature and normalization for the collisional plasma model, and the temperatures of the solar wind ionization population (assuming equilibrium) and the normalizations. The temperature of the LHB component ( $1.10 \pm 0.07$  MK) is in agreement with values predicted from MHD models<sup>7</sup>, but the total LHB creates only 25% of the total 0.1–0.4 keV flux, so the implied LHB pressure is reduced by a factor of two. Removing the LHB component entirely results in a significantly (F-test probability of  $3 \times 10^{-7}$ ) worse fit.

The implied ion balance temperatures for the fast solar wind is  $0.8 \pm 0.1$  MK, while that of the slow solar wind is  $3.3 (-0.5, +0.8)$  MK, in rough agreement with existing observations<sup>14</sup>. With only a single spectrum of modest resolution, we cannot fit each element or ion independently, which would allow us to measure the ionic composition and abundances in the solar wind directly. The DXS look direction is at  $\sim 10^\circ$  in Galactic latitude, a direction that must be dominated by local emission due to the large Galactic

column density. The relative contributions of the SWCX (75%) and LHB (25%) emission are in line with earlier detailed heliospheric models<sup>9</sup> that used more limited spectral codes.

Our model predicts only three observable features in the CHIPS band. These include the Fe IX line at 171.1Å (model 6.1 LU, observation ~6 LU) and two O VI line complexes at 173Å (10.2 LU) and 150Å (9.0 LU). If present consistently throughout the CHIPS observations these lines would have been detected, but we note that the DXS spectrum contains only ~25 ksec of data and so these lines could be weaker on average. At higher energies, the model predicts O VII emission of ~2.4 LU and O VIII of ~2.6 LU which are within or only slightly above the range of observed values<sup>15</sup>.

These results demonstrate that fitting the soft X-ray background requires both SWCX and thermal emission and that the CHIPS and DXS results are not inherently in disagreement. However, the model does predict strong oxygen lines at levels that have been seen but only sporadically. Beyond explaining the origin of the soft X-ray band emission, this result shows that long-term observations with good spectral resolution in this bandpass would allow indirect measurement of solar wind ions along any sightline, including at high-ecliptic latitudes where direct measurements are extremely difficult. Although intended for astrophysics, the upcoming launches of the Spektrum X-Gamma all-sky survey and the Astro-H microcalorimeter missions may thereby provide useful heliospheric data as well. Future high-resolution X-ray satellites could measure CX in the astrospheres of other stars, directly measuring stellar mass loss and composition.

## Method

Our approach does not require detailed atomic models of the charge exchange emission process as a function of collision velocity and energy level, a challenging calculation that must be done for each ion individually. Instead, the problem is separated into individual components. Astrophysical X-ray charge exchange emission typically occurs when neutral hydrogen (or helium) loses an electron to a highly-ionized ion, usually into a high principal quantum number state which then decays radiatively. The total SWCX emission along any line of sight depends upon the composition, density, and relative velocities of (i) the solar wind ions and (ii) the neutral material (either H or He), together with (iii) the cross section into each possible level and (iv) and the subsequent radiative cascade. Existing models<sup>8,9</sup> have focused on addressing (i,ii) while noting that many more atomic calculations (iii, iv) are needed. These models and the observational data confirm that while the SWCX component does vary, the total flux only changes by at most a factor of two to three and that predicting these variations is difficult.

Our approach focuses on modeling (iv), the radiative cascade itself, for all relevant ions to get the best possible prediction for the emitted spectrum. For all ions abundant in the solar wind, we extended the existing AtomDB<sup>12</sup> database of radiative rates and wavelengths with new calculations using the Autostructure<sup>16</sup> code. These new calculations extend the peak principal quantum number from a typical value of  $n=5$  up to in some cases  $n=13$ . We assume the exchanged electron is initially in a principal quantum number state<sup>17</sup> given by a simple analytic function of the ion charge and ionization energies of the neutral atom (either H or He) and ion respectively (if not an integer, a weighted sum of the adjacent levels is used). For the orbital angular momentum, we considered two other models, the 'Separable' and the Landau-Zender methods<sup>17</sup>. Although both approaches provided generally similar results in the soft X-ray and EUV bands, we chose to use the 'Separable' method for this work. We assumed the heliospheric neutral component was 10% He, as the DXS line of sight was at ecliptic latitude ~90° and did not intersect the He focusing cone<sup>8</sup>.

## References



1. Sanders, W. T., Edgar, R. J., Kraushaar, W. L. McCammon, D., Morgenthaler, J. P. Spectra of the 1/4 keV X-ray Diffuse Background from the Diffuse X-ray Background Experiment. *Astrophys. J.* 554, 694-709 (2001)
2. McCammon, D. & Sanders, W. T. The soft X-ray background and its origins. *Ann. Rev. Astron. & Astrophys.* 28, 657-688 (1990)
3. Hurwitz, M., Sasseen, T. P., Sirk, M. M. Observations of Diffuse Extreme-Ultraviolet Emission with the Cosmic Hot Interstellar Plasma Spectrometer (CHIPS), *Astrophys. J.* 623, 911-916 (2005)
4. Cravens, T. E. Comet Hyakutake x-ray source: Charge transfer of solar wind heavy ions. *Geo. Res. Letters*, 24, 105-108 (1997)
5. Cox, D. P. Modeling the local bubble, in *The Local Bubble and Beyond*, edited by D. Breitschwerdt, M. J. Freyberg, and J. Trümper, p. 121, Springer-Verlag, New York, 1998
6. Snowden, S. L., McCammon, D., Burrows, D. N., Mendenhall, J. A. Analysis procedures for ROSAT XRT/PPSP observations of extended objects and the diffuse background, *Astrophys. J.*, 424, 714-728 (1994)
7. Smith, R. K., Cox, D. P. Multiple Supernova Remnant Models of the Local Soft X-ray Background, *Astrophys. J. Supp. Series*, 134, 283-309 (2001)
8. Cravens, T. E. Heliospheric X-ray Emission Associated with Charge Transfer of the Solar Wind with Interstellar Neutrals, *Astrophys J.* 532, L153-L156 (2000)
9. Koutroumpa, D., Lallement, R., Raymond, J. C., Kharchenko, V. The Solar Wind Charge-Transfer X-ray Emission in the 1/4 keV Energy Range: Inferences on Local Bubble Hot Gas at Low Z, *Astrophys. J.*, 696, 1517-1525 (2009)
10. Bloch, J. J., Roussel-Dupre, D., Theiler, J., Johnson, E. Limits on the Emission from Fe VIII- XII in the Hot Local Interstellar Medium, *ASP Conference Series*, Vol 264, 243-251 (2002)
11. McCammon, D. et al. A High Spectral Resolution Observation of the Soft X-ray Diffuse Background with Thermal Detectors, *Astrophys. J.* 576, 188-203 (2002)
12. Foster, A. R., Ji, L., Smith, R. K., Brickhouse, N. S. Updated Atomic Data Calculations for X-ray Spectroscopy, *Astrophys. J.*, 756, 128-138 (2012)
13. Savage, B. D., Sembach, K. R. Interstellar Abundances from Absorption-Line Observations with the Hubble Space Telescope, *Ann. Rev. Astron. Astrophys.*, 34, 279-330
14. von Steiger, R., Schwadron, N. A., Fisk, L. A., Geiss, J., Gloeckler, G., Hefti, S., Wilken, B., Wimmer-Schweingruber, R. F., Zurbuchen, T. H. Composition of quasi-stationary solar wind flows from Ulysses/Solar Wind Ion Composition Spectrometer, *J. Geophys. Res.*, 105, 27217-27238 (2000)
15. Koutroumpa, D., Acero, F., Lallement, R., Ballet, J., Kharchenko, V. OVII and OVIII line emission in the diffuse soft X-ray background: heliospheric and galactic contributions, *Astron & Astrophys*, 475, 901-914 (2007)
16. Badnell, N. R. Dielectric recombination of Fe(22+) and Fe(21+), *J. Physics B*, 19, 3827-3835 (1986)
17. Janev, R. K., Winter, H. State-selective electron capture in atom-highly charged ion collisions, *Physics Reports*, 117, 265-387 (1985)

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